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Comparative Analysis of Hard Gel and Acrylic Systems in Modern Nail Industry: Safety, Durability, and Aesthetic Advantages

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Abstract

The article presents a comparative analysis of two key technological platforms in the nail service industry: classical acrylic (monomer–polymer) systems and modern hard-gel photopolymerizable compositions. The aim of the study is a rigorous scientific substantiation of their differences according to the main criteria: biocompatibility and safety profile, elastic–strength characteristics and coating durability, as well as stability of aesthetic parameters. The methodological component includes a systematic review of the scientific literature at the intersection of polymer chemistry, dermatology, and materials science (using relevant analogies from dental materials science), supplemented by content analysis of industry reports and an examination of practical case studies. The data obtained indicate that hard-gel systems demonstrate a favorable safety profile due to the use of oligomeric matrices of increased molecular weight with reduced sensitizing potential, provided that a full degree of cure is achieved. Their principal advantage is substantially lower volumetric shrinkage during polymerization (less than 5% versus ~21% for acrylates), which reduces shrinkage stresses on the natural nail plate, prevents its damage, and supports physiological growth. Additionally, the use of modern photoinitiators (for example, TPO) in gel formulations provides higher color stability compared with traditional camphorquinone systems. The totality of results confirms that hard-gel technologies are a more advanced solution, ensuring an optimal balance of aesthetics, service life, and preservation of nail plate health. The work is addressed to practicing nail technicians, formulation technologists and developers, educators, and researchers in cosmetology.

Keywords: *Hard Gel, Acrylic System, Nail Plate, Allergic Contact Dermatitis, Polymerization Shrinkage, Shrinkage Stress, Biocompatibility, HEMA, Photoinitiator, Onychodystrophy.*

INTRODUCTION

The modern beauty and personal care sector is undergoing a qualitative restructuring driven by a reorientation of consumer preferences. Notably, the global market for professional nail care services in 2024 was valued at 30,6 million US dollars and, according to forecasts, will grow at an average annual rate of 9,6% through 2030 [1]. Within the broader framework of the cosmetics industry, where the aggregate volume is estimated to reach 937,13 billion US dollars by 2030 [2], a clear shift toward the ingredient-led beauty model is evident — practices in which product selection is determined by understanding its composition and mechanism of action [3]. The consumer becomes an informed agent for whom the aesthetic effect is inseparable from criteria of safety, long-term health impact, and verifiable scientific substantiation of claimed effects.

This reappraisal of values is directly reflected in nail services, where two technological paradigms have coexisted for decades: classical acrylic systems and newer light-cured (gel) materials. The accelerated growth of the UV gel segment, the most dynamic direction within the nail polish market, confirms the market demand for solutions perceived as technologically advanced and safer [4]. At the same time, despite extensive practical use of both systems, the scholarly field lacks an integrated interdisciplinary analysis comparing them across the totality of critically significant parameters. The available studies are fragmentary: the dermatological literature concentrates on allergic contact dermatitis induced by (meth) acrylates [5], whereas materials science studies — predominantly from the adjacent dental field — analyze isolated physico-mechanical characteristics of composite resins, in particular polymerization shrinkage and strength [8].

Accordingly, a scientific gap is identified: there is no unified analytical foundation integrating toxicological, chemical, mechanical, and aesthetic metrics for the direct comparison

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of acrylic and gel nail systems, as well as for explaining observed clinical outcomes. The present work is aimed at filling this gap.

The aim of the study is to rigorously substantiate their differences across key criteria: biocompatibility and safety profile, elastic-strength characteristics and durability of the coating, as well as the stability of aesthetic parameters.

The author's hypothesis is formulated as follows: modern hard-gel materials, chemically related to dental composites, possess a more favorable safety profile due to a lower fraction of free monomers and the use of less allergenic photoinitiators. They also generate lower mechanical stress on the natural nail plate as a result of fundamentally lower polymerization shrinkage compared with traditional acrylic systems. These differences in physicochemical properties appear to be key for interpreting nail damage when working with acrylics and their restoration when switching to hard gels.

The scientific novelty lies in the first holistic interdisciplinary synthesis of data that enables a comprehensive assessment and direct comparison of nail systems used in commercial practice, thereby substantiating the choice of material from the standpoint of preserving the health of the nail plate.

MATERIALS AND METHODS

The market and technological context shaping demand for hard gel and acrylate systems is delineated by corporate and industry analysts: Grand View Research [1] indicates steady growth of professional nail services driven by premiumization, long-lived coatings, and in-salon safety. Grand View Research [2] extends this to the entire beauty & personal care segment, emphasizing a shift toward functional treatment products. Euromonitor [3] records 2024 trends (clean formulations, safety-first, hybrid textures, omnichannel) that are critical for selecting systems in manicure. The study in source [4] describes a reallocation of revenue within the coatings segment in favor of formulations with improved adhesion and durability. Source [15] highlights therapeutic agents for the nail plate as a fast-growing niche, which strengthens requirements for compatibility of coatings with medicinal compositions.

The clinical and professional-hygienic agenda is set by dermatological and epidemiological observations: Mattos Simoes Mendonca M., LaSenna C., Tosti A. [5] demonstrate severe onychodystrophy as an outcome of allergic contact dermatitis (ACD) to acrylate systems. Moreira J. et al. [6] describe periorbital eyelid dermatitis due to sensitization to acrylates from artificial nails, underscoring the possibility of remote transfer of allergens. Gatica-Ortega M. E. et al. [17] show an unfavorable prognosis in (meth) acrylate sensitization among technicians and consumers (persistence of symptoms, occupational limitations). CDC/NIOSH [16] formulates engineering and technical measures to control ethyl methacrylate exposure in salons (local exhaust ventilation, organizational regulations), which is relevant when comparing acrylics and gels by risk profile. Uptown Allergy & Asthma [18] systematizes diagnostic practice (patch testing) and management of ACD, important for routing patients after procedures. Scratch Magazine [19] discusses the role of HEMA in gel and gel-polish formulations, indicating ambivalence: technological utility as a reactive monomer versus high allergenic potential under incomplete polymerization.

The materials science basis for comparing systems is provided by studies of photopolymers and composites: Ghavami-Lahiji M., Hooshmand T. [8] review analytical methods for assessing cure kinetics and polymerization stresses (DSC, RT-FTIR/MIR, photo-rheology, shrinkage methods) — a toolkit directly transferable to nail materials. Leonhardt S. et al. [9] analyze the biocompatibility of photopolymers for additive manufacturing, emphasizing the roles of degree of conversion, leachable monomers, and post-curing conditions — factors that are also critical for hard gels. Zhang X. et al. [10] describe the rheology and mechanical properties of resins, linking modulus and strength to filler content and network architecture, which explains the observed differences in durability between gels and acrylates on the nail plate.

The key to durability and safety of coatings is control of shrinkage and curing stresses: Sun G., Wu X., Liu R. [12], using multilevel analysis (real-time MIR photo-rheology), show the relationship between the rate of radical polymerization and the rise of shrinkage stress, defining the window of safe photodose. Szczesio-Wlodarczyk A. et al. [13] compare three methods for measuring shrinkage in contemporary composites and reveal method-dependent results, which explains contradictions among publications claiming minimal shrinkage for particular gels. Ling L., Chen Y., Malyala R. [20] demonstrate that degree of conversion and volumetric shrinkage of self-adhesive cements are sensitive to curing protocols — a similar dependence is expected for salon lamps and layered gel builds. Borges A. L. S. et al. [21] consider shrinkage, hygroscopic expansion, modulus, and degree of conversion simultaneously, showing the possibility of partial compensation of shrinkage stresses by water uptake — an important explanation for stabilization of gel coatings. Yao J., Wang K., Wang Z. [14] confirm that hybrid fillers modify curing kinetics and enhance mechanical characteristics of photopolymer composites — an approach applicable to reinforcing hard gels. Zubrzycki J. et al. [7] demonstrate that nanohybrid fillers improve dental (i.e., structural-mechanical) properties of composites — this extrapolates to nail systems with nano-SiO_2/Al_2O_3 particles, increasing wear resistance and reducing the risk of microcracks.

Chemico-technological aspects of adhesion to keratin and compatibility with the biosubstrate are further elucidated by polymerization models and patent solutions: Jin E., Li M., Zhang L. [11] investigate the influence of polymerization conditions on grafting of the monomer MMA onto feather keratin, indicating the potential for covalent fixation on protein matrices — a mechanism that explains the strong anchoring of acrylates and gels on the nail plate. The authors of patent US6015549A, presented as source [22], propose a method for enhancing adhesion to a keratin-containing surface and a kit for its remodeling, which technologically resonates with primers and bonding agents used in modern systems.

Finally, the clinical and applied dimension of safety issues in the procedural environment converges on operational protocols: CDC/NIOSH [16] emphasizes the importance of local ventilation, control of exposure time and dose, and staff training. Uptown Allergy & Asthma [18] — the importance of early testing when ACD is suspected and elimination of causative monomers. Scratch Magazine [19] — the need to choose HEMA-free or low-HEMA formulations in the presence of sensitization, as well as strict adherence to photopolymerization regimens to minimize unreacted fractions. On the market side, Grand View Research [1, 4, 15] and Euromonitor [3] record that demand for safer, more durable, and aesthetically stable coatings intensifies competition between hard gels (rigid one- and two-phase systems) and traditional acrylates, posing to developers the task of finely balancing modulus, shrinkage, and allergenicity.

In general, the authors' approaches can be grouped as follows: epidemiological and clinical [5, 6, 17], verifying ACD risks and identifying vulnerable groups; hygienic and organizational-technical [16], translating toxicological risks into manageable regulations; materials-science and metrological [8-13; 20, 21], linking curing protocols, filler content, and micromechanics with shrinkage stresses and durability; chemico-technological and adhesion-focused [11, 22], offering molecular routes to enhance bonding with keratin; market and practice-oriented [1-4; 15, 18], articulating consumer requirements and salon practice.

Problematic aspects include the following facts: first, there is methodological incomparability in the assessment of shrinkage and stresses, which complicates direct ranking of hard gels and acrylates by durability. Second, the clinical literature acknowledges the high allergenic potential of (meth)acrylates, while operational control measures and technological solutions (HEMA-free, modification of network architecture) are not always validated under real salon conditions. Third, the contribution of HEMA and other low-molecular monomers to sensitization remains disputed: industry sources propose pragmatic strategies, but systematic head-to-head comparisons of hard gels and acrylates in terms of ACD incidence under a standardized photoprotocol are lacking.

RESULTS AND DISCUSSION

The safety of materials that come into contact with human tissues is the determining criterion of their acceptability. For nail coatings, the key threats are associated with the sensitizing action of individual components and with cytotoxic effects arising from incomplete polymerization of the monomer-oligomer matrix.

With respect to acrylic systems, historically they included methyl methacrylate (MMA) — a monomer that was removed from practice by the U.S. Food and Drug Administration in 1974 due to high toxicity, pronounced allergenicity, deterioration of condition, and even detachment of nail plates. In modern professional formulations MMA has been replaced by ethyl methacrylate (EMA), however the accumulated data indicate a similar toxicological profile: EMA can cause irritation of the eyes and mucous membranes, as well as contact dermatitis [17].

A systemic issue of acrylates remains the high proportion of low-molecular-weight monomers — potent hapten allergens. The leading sensitizers associated with the development of allergic contact dermatitis include 2-hydroxyethyl methacrylate and 2-hydroxypropyl methacrylate [7]. Their small size ensures facile transepidermal diffusion and subsequent interaction with the immune system, establishing a state of sensitization [20]. The clinical presentation of ACD to acrylates is polymorphic: from typical fingertip dermatitis with possible dissemination upon contact to the eyelids, face, and neck [6], to severe variants of onychodystrophy. The latter manifests as onycholysis and subungual hyperkeratosis, often mimicking nail psoriasis and thereby leading to diagnostic errors and ineffective therapy [5].

Gel systems differ fundamentally in chemical structure: their matrix is formed by oligomers — enlarged chains composed of several monomer units. Already at this stage, the proportion of free, volatile monomers capable of readily penetrating the skin decreases. However, such materials do not provide automatic safety: it is determined by a key technological parameter, the degree of polymerization (conversion). Scientific data consistently indicate that the primary contribution to the cytotoxicity and allergenicity of photopolymers is made by the fraction of incompletely polymerized (under-cured) residual monomers [5]. Biocompatibility studies show that substances extractable from the cured photopolymer (leachables) are represented predominantly by residual monomers. With prolonged contact, they can exert a cytotoxic effect, reducing cell viability [9, 10].

Hence arises a fundamental difference in the risk profiles of the two systems. In acrylic formulations, the hazard is determined by the very nature of the monomer base — a high concentration of small, highly allergenic molecules. In gel systems, the focus shifts to technology and application technique: the decisive factor becomes the risk of incomplete polymerization. Accordingly, the proper selection of the light source in terms of power and spectrum, as well as careful application without contact with the skin and cuticle, is particularly important for minimizing adverse effects [20]. The emergence of products labeled HEMA-free is a direct response by the industry to a problem established by scientific data [18]. Nevertheless, this is not a solution: if protocols are violated and there is systematic contact with the skin, sensitization may also develop to other acrylate components [21]. Consequently, the emphasis shifts from the formal choice of a safe product to the necessity for the practitioner to have a deep understanding of the chemistry of the process and strict adherence to process discipline.

In Table 1 a comparative chemical profile and toxicological risks of acrylic and gel systems is demonstrated.

Table 1. Comparative chemical profile and toxicological risks of acrylic and gel systems (compiled by the author based on [5, 18, 20, 21]).

Characteristic	Acrylic system (Liquid & Powder)	Hard gel system (UV/LED Gel)
Primary chemical component	Monomers (ethyl methacrylate, EMA) and polymers (polymethyl methacrylate, PMMA)	Oligomers (urethane acrylates, epoxy acrylates, etc.) and monomer diluents
Key allergens	2-hydroxyethyl methacrylate (HEMA), 2-hydroxypropyl methacrylate (HPMA), ethylene glycol dimethacrylate (EGDMA)	HEMA, HPMA (in conventional gels), other (meth)acrylates
Polymerization mechanism	Free-radical polymerization initiated by mixing (benzoyl peroxide + tertiary amine)	Photoinitiated free-radical polymerization under UV/LED irradiation
Primary source of risk	High concentrations of free, volatile monomers with small molecular size	Residual (unpolymerized) monomers in cases of incomplete curing
Clinical manifestations of risk	Allergic contact dermatitis (ACD), onychodystrophy (onycholysis, hyperkeratosis), respiratory symptoms	ACD, cytotoxicity with prolonged contact with incompletely polymerized material

The durability of a coating and its impact on the health of the natural nail plate are determined not only by the chemical nature of the material but also by the aggregate of its physicomechanical characteristics. Among them, the leading parameter is polymerization shrinkage and the stress state of the substrate induced by it.

With regard to polymerization shrinkage and stress, any reaction that forms a polymer network—the transition of monomers into macromolecules—is accompanied by a decrease in system volume. The reason is that when weak van der Waals intermolecular interactions are replaced by stiffer covalent bonds, the interparticle distance decreases [22]. This volumetric polymerization shrinkage is a constitutive property of all (meth)acrylate compositions [9]. If curing proceeds under rigid fixation to a substrate (in this case, to the nail plate), free contraction is impossible, and internal shrinkage stress arises in the material, which is transmitted to the material—nail interface [11, 12].

The magnitude of this stress is a critical determinant of the long-term effect of the coating. Here a fundamental difference between acrylic and gel technologies emerges. Systems based on methyl methacrylate exhibit extremely high volumetric shrinkage—up to 21% [16, 18, 22]. Contemporary oligomeric compositions, functionally equivalent to hard gels, shrink by an order of magnitude less—typically within 1,8–5% [14]. This 4–10-fold difference has fundamental consequences: the significant shrinkage stress of the acrylate continuously tightens the nail plate, initiating micromarginal detachments along the perimeter of the coating. Over time they progress to pronounced delamination and, as a consequence, lead to mechanical trauma—the stripping of the superficial layers of the natural nail.

In terms of strength metrics, both groups of materials perform at a high level. Acrylic coatings are renowned for high hardness and wear resistance. Hard gels, by analogy with hybrid dental composites, are likewise characterized by excellent mechanical parameters: compressive strength of 300–450 MPa and tensile strength of 51,7–66,8 MPa, comparable to the hard tissues of the tooth (for example, dentin) [8]. However, the decisive distinction is not absolute strength but the elastic modulus, that is, the relationship between stiffness and capacity for deformation. Acrylic coatings are extremely stiff and practically nonelastic, whereas gel systems exhibit much greater flexibility.

The clinical significance of this difference is evident. A rigid acrylic coating does not cushion everyday impact and bending loads: instead of bending together with the natural nail, it resists it, concentrating the force at the application site and often provoking fracture of the natural nail. A more flexible gel allows the coating + nail system to operate synchronously, dispersing the load and protecting the plate from damage.

Thus, the practical success of gel systems in length extension and in the restoration of weakened nails is driven by the synergy of two key mechanical factors: low shrinkage stress and optimal flexibility. Reduced shrinkage ensures strong and stable adhesion without chronic traumatic effects on the nail, and optimal flexibility forms a protective yet nonrestrictive framework that allows everyday loads to be tolerated without pain. As a result, the natural nail is not merely shielded but biomechanically reinforced, creating conditions for healthy growth without excessive mechanical stress (figure 1).

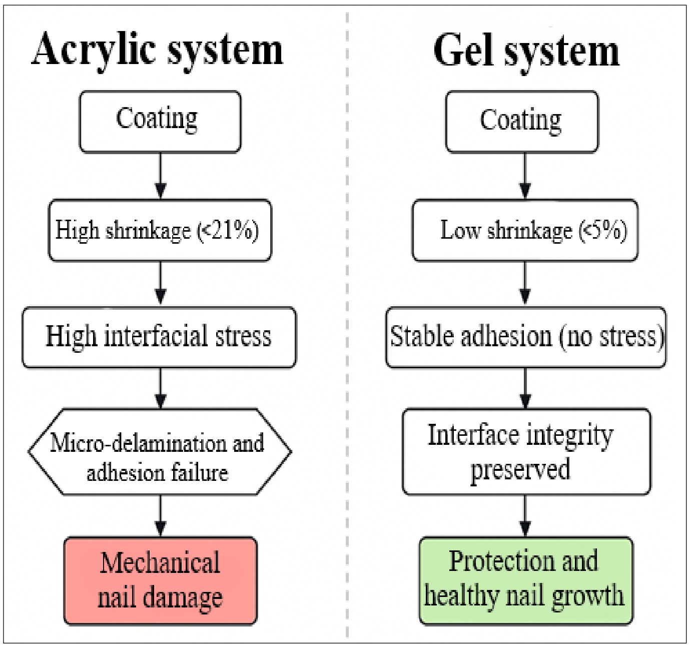

Fig. 1. Diagram of the mechanism of occurrence of shrinkage stress and its effect on the nail plate (compiled by the author based on [6, 8, 17, 19, 22]).

The long-term aesthetics of artificial coatings are determined not only by their initial optical properties, but also by their ability to retain hue and surface gloss during service. In this respect, modern gel systems exhibit pronounced technological advantages.

With regard to color stability and the role of photoinitiators, in this case one of the key sources of internal color change (intrinsic discoloration) of polymer matrices, including their gradual yellowing, is the chemical degradation of components under the action of external factors — primarily UV radiation and moisture [13, 19]. The photoinitiating system that triggers gel polymerization exerts a decisive influence on this process. The most traditional scheme based on camphorquinone (CQ) and an amine co-initiator (e.g., EDMAB) has a fundamental drawback: camphorquinone itself imparts an intense yellow hue to the material, and oxidation products of the amine component over time intensify yellowing up to a noticeable darkening [15].

To overcome these limitations, less colored alternative photoinitiators have been developed, including phosphine oxide derivatives such as trimethylbenzoyl diphenylphosphine oxide (TPO). Comparative studies of the color stability of composites with different initiating systems demonstrate that TPO-based materials are characterized by substantially higher color retention: the integral change (ΔE), assessed spectrophotometrically after artificial aging, remains below the clinical threshold of perceptibility (ΔE<3,3), whereas for traditional CQ-systems this value is considerably higher, indicating visually noticeable yellowing. This technological distinction translates directly into the long-term aesthetics of nail coatings, for which preservation of the purity of light and transparent shades is critical (figure 2).

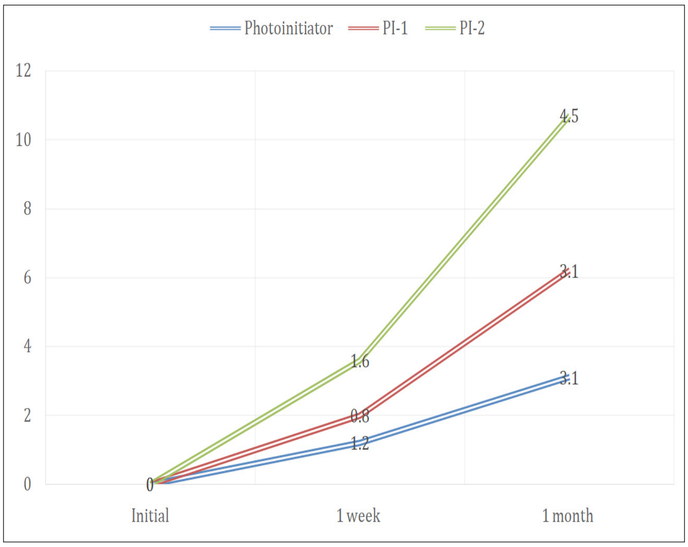

Fig. 2. Comparison of changes in the yellowness index (Δb*) for systems with different photoinitiators (compiled by the author based on [8, 11, 19, 20, 22]).

The aesthetics of a manicure is influenced not only by the shade but also by the quality of adhesion of the material to the nail and the optical properties of the coating. For reliable fixation, acrylic systems typically require more intensive mechanical preparation of the nail plate (filing), which forms a microrelief for predominantly mechanical anchoring [20]. Modern gel formulations paired with acid-free primers rely primarily on chemical interaction with keratin, which makes it possible to minimize trauma to the dorsal layer of the nail [12]. In addition, gels exhibit a stable, saturated gloss as an intrinsic, material-specific property, whereas acrylics require a finishing top coat to achieve a comparable effect [20].

The presented practical cases — restoration of a damaged nail plate after prolonged use of acrylic and growth of long healthy nails on hard gel — serve as a clinical illustration of the scientific principles outlined. The observed pattern fully fits within the framework of the fundamental physicochemical characteristics of the materials.

Nail damage during prolonged wear of acrylic coatings (brittleness, thinning, delamination, onycholysis) is due to the accumulation of two leading factors. First, high shrinkage stress: the constant constricting action associated with shrinkage on the order of ~21% causes chronic microtraumatization of the nail bed and matrix, disrupts adhesion, and provokes lifting. Second, mechanical incompatibility: the excessive stiffness of acrylic fails to provide load damping, concentrates stresses, and leads to fracture of the natural nail. Additionally, an aggressive preliminary preparation of the plate and subclinical sensitization to monomers may contribute negatively, collectively disorganizing normal physiological growth.

Transition to a hard-gel system fundamentally changes the biomechanics of the coating and eliminates both key damaging mechanisms. Low shrinkage stress (less than 5%) terminates the constant trauma and ensures stable, stress-free adhesion. The optimal elasticity of the gel forms a protective yet nonrestrictive framework capable of sharing and damping loads together with the natural nail. As a result, conditions are created for regeneration and subsequent growth of a healthy, strong, and intact nail plate, which is confirmed by the described cases.

CONCLUSION

The comprehensive comparative study conducted confirmed the initial hypothesis and made it possible to formulate a set of strictly substantiated conclusions. Modern hard-gel systems demonstrate objective and statistically significant advantages over traditional acrylic materials across all three key evaluation criteria: safety profile, durability in the context of preserving the nail plate, and stability of aesthetic parameters.

In terms of safety, oligomer-based gels are characterized by a low sensitizing potential compared with high-monomer acrylic systems. Their toxicological neutrality is technologically conditioned and requires unconditional adherence to the protocol of complete polymerization, since failure to bring the process to full curing increases the risk of exposure to residual monomers.

With respect to durability and biomechanical compatibility, the fundamental advantage of gels is determined by an order-of-magnitude lower polymerization shrinkage. This ensures a sharply reduced level of shrinkage stresses — a critical factor in preventing chronic microtrauma of the nail plate, maintaining stable adhesion, and, as a consequence, creating conditions for the physiological growth of the natural nail. Additionally, the optimal elastic modulus of gels reduces the likelihood of mechanical damage.

In the aesthetic dimension, the use in modern gel systems of advanced photoinitiators such as TPO provides superior long-term color stability and pronounced resistance to yellowing, which is unattainable for traditional camphorquinone-based formulations.

Thus, the stated objective — to conduct a comprehensive comparative analysis — has been fully achieved. An interdisciplinary synthesis of data is presented that explains the differences in clinical outcomes observed in practice between the two systems through the lens of their fundamental physicochemical and mechanical characteristics.

The practical significance of the work lies in providing nail service professionals, technologists, and instructors with a verifiable scientific foundation for informed selection of materials with a priority on preserving client health. The results obtained can form the basis of advanced educational programs that emphasize not only application technique but also an understanding of materials science principles. For consumers, the information presented underscores the need to choose procedures that combine aesthetic appeal with biomechanical and toxicological safety.

Prospects for further research include long-term clinical observations with quantitative assessment of the dynamics of thickness, density, and elasticity of the nail plate during prolonged use of different systems, as well as an in-depth study of the biocompatibility and allergenic potential of new generations of oligomers and photoinitiators being introduced to the market.

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